Challenges, Barriers, and Priorities for Nanomaterials Metrology

- **Summary of issues conveyed in plenary talks and in breakout session talks.**
- **Bob Keller's selective observations**

- **Susan Holl's (and others') observation:**
  - **We care about different technologies and reliability concerns, but are addressing the same problems.**

Nanomechanical Issues in Fabrication: General Technological Challenges and Materials Barriers

Technological

- Each device has its own unique reliability issues.
- High yield, uniformity, reliability over 20 years
- Failure mode analysis should lead to info useful for re-design
- Acceleration factor < 10 desired
- Tools/techniques: measure nm motion, addressing 6 DoF, faster than device resonance frequency
- Automated assembly ineffective for < 0.5 mm (5 x 10^5 nm …)
- Go digital! Atomically precise engineering
  - Need tools!
  - Pattern ALD, using STM?
- Stuck in 2-D! SPM…
- Need for speed… characterization
  - Solution: XRD?
- Need metrology for structure of low-level lines, esp. early in the process
- Tools capable of multiple measurements:
  - Thickness, crystalline phase, texture
- Large Area Temperature control

Materials

- MEMS: stiction, friction, wear
  - Solution? Non-contacting parts
- Fatigue
  - Solution? Conservative design stress
- Creep
- Hinge memory
- Stress: absorb, balance, control
- CNTs: problems
  - Dimensional uniformity, defects
  - Separate by electronic structure
  - Can't make continuous fibers
  - Need much better process control and qualification
- Nanocomposites
  - Need better understanding, using both simulation and experiments, esp. CNT/matrix interface
- QDs:
  - Need uniform size distribution
  - Need uniform spacing
  - Control plasticity
  - Nanopatterning by FIB?

More Generally…

- Make small things with more control
  - Size uniformity
  - Defect control
- Patterning at nanoscale
  - QDs
  - ALD layers

Nanomechanical Issues in Manufacturing
Breakouts

Technological

- Develop relationships between *in-situ* tests and real failures
- Local temperature measurements?
  - Solution: micro-Raman?
- Coupled measurements
- Resolution:
  - Space, energy
- *In-situ*, coupled measurements
  - Optical/mechanical
  - Electrical/mechanical
- More modeling! (coupled with lab equipment)
- More collaborations;
  - Manufacturing development & materials characterization/metrology development

Materials

- Structure/property relationships for monolayers (adhesion, friction, wear)
- Effects of surface roughness
- Mechanical integrity of poly-Si vs. metals
- Develop process variables = f(σ_{res}, stress gradients, σ_{ys}, UTS)
- Structure uniformity, defects in coatings for MEMS
- Wear: sliding and impact
- Know where all the atoms are
- Bulk properties:
  - Elastic, dielectric, DOS
- Gradient characterization (chemical, physical), in complex matrices

Nanomechanical issues in Manufacturing
Breakouts 2

Technological

- Faster, higher resolution imaging/morphology
  - SEM, AFM, TEM
- Separation, purification methods
- Inline-capable techniques for CMP:
  - Particle size, morphology, dispersion, aggregation, correlation to performance
- High-throughput adhesion measurement
- New tests/models for new material combinations
- High temperature interfacial reliability:
  - Segregation, voiding
- Multiple high-resolution techniques
- Nanoscale strain measurement
- Nanoscale electrical characterization
- Nanoscale structure size/shape
- Non-destructive measurement of defects
- Deconvolute sample-probe interaction

Materials

Nanomechanical Issues in Characterization and Testing General Technological Challenges and Materials Barriers

Technological

- Instrument consistency for E, H
- Small length scales
  - Difficult measurement problems even with state of the art instruments
- Need good test samples:
  - No dislocations, surface defects
- Tip/sample interaction energies need to be understood
  - Contact area effects
- “Desperately needed”:
  - Hi-res, *in-situ* deformation in electron microscope
- Accurate and Proven AFM technology!
- Better control of SPM tip motion, I.e. no unintentional lateral motion
- The perfect AFM:
  - Accurate knowledge of F and d for AFM
  - F sensor perpendicular to surface
  - Sharp, durable tip

Materials

- In general (Fall ‘04 MRS):
  - Size effects, temp or viscoelasticity, multiscale modeling, adhesion/surface energy
- Difficult to separate stress and temperature effects on stress-strain behavior

Nanomechanical Issues in Characterization and Testing General Technological Challenges and Materials Barriers 2

Technological

- The perfect AFM (continued)
  - F sensor with stiffness control for both mechanical properties and topography
  - Easy switch between F and d control
  - Wide range of operational frequencies, temperature
  - High-bandwidth, low-noise pre-amp
- MUST combine experiment and modeling for adhesion/interfacial fracture
- Direct imaging of contact areas

Materials

- Need more than incremental advances in models/tests for adhesion, beyond modification of existing tests
  - Revolutionary, not just evolutionary? (BK)

Nanomechanical issues in Characterization and Testing

Breakouts

Technological

- Scaling of test methods to sub-micrometer samples:
  - Uniaxial, multiaxial, torsion
  - Deformation mapping
  - Gripping, manipulation
- Rapid, fully automated fabrication methods
- Calibration standards for nano-test equipment
- Localized strain measurement
- Nanoindenter tip geometry control
- Better FIB resolution (SE imaging)
- Experimentation on nanoscale biological materials
- Sub-micrometer scale toughness measurements, standards
- Measurement of stress gradients, esp. over small dimensions
- Sub-micrometer temperature measurement (direct)
- Microforce standards

Materials

Nanomechanical issues in Characterization and Testing

Breakouts 2

Technological

- Improvements in spatially resolved characterization:
  - SEM, SIMS, *in-situ* TEM, microdiffraction, micro-Raman
- Need better characterization of:
  - AFM tips
- Need AFM and model velocities to match

Materials